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Anomalous scattering of high power millimetre waves from gyrotrons in tokamak plasmas is investigated. During injection of gyrotron power up to 600 kW in X-mode, spectral power densities of MeV have frequently been recorded by radiometers at the TEXTOR tokamak [Westerhof 2009, Nielsen 2013]. The majority of the anomalous radiation is downshifted in frequency with respect to the gyrotron frequency. Varying the radiometer line-of-sight shows that a large fraction of the radiation is generated along the gyrotron beam in the region where the gyrotron frequency matches twice the upper hybrid frequency. The radiation levels are strongly enhanced during MHD activity, such as magnetic islands, and scale non-linearly with gyrotron power. Furthermore, the anomalous radiation is present both with and without an electron cyclotron absorbing resonance layer in the plasma and has been reproduced on several tokamaks and with several different gyrotron frequencies. A detailed understanding of the anomalous scattering will clarify whether the underlying interaction could influence the heating and current drive efficiency in tokamaks, and if the processes can be used for plasma diagnostic purposes.

At TEXTOR, the anomalous scattering was studied during 2nd harmonic Electron Cyclotron Resonance Heating (ECRH) at 140 GHz (X-mode) at a gyrotron power ranging from 200 to 600 kW. The scattering signal was measured using the modified collective Thomson scattering (CTS) receiver [Nielsen 2012] and the inline receiver [Oosterbeek 2008] as illustrated in Fig. 1. The CTS receiver consists of a heterodyne detection system equipped with two narrow notch filters for direct protection against gyrotron stray radiation. The signal is detected with 42 frequency channels ranging from 136 to 142 GHz. The level of the anomalous scattering reached several MeV, was highly non-linear with respect to gyrotron power, and was amplified significantly in the presence of a rotating 2/1 mode. The dynamic ergodic divertor (DED) was used to create rotating m/n = 2/1 islands by applying an AC current with a frequency of 974 Hz. The mode locked to the rotating field created by the DED which allowed us to study the anomalous scattering in a controlled manner.

A number of discharges were performed with a fixed scattering geometry in which the ECRH power, the plasma density and the toroidal magnetic field were varied. The 2nd harmonic ECE resonance position was varied from high-field side power deposition to central and low-field side power deposition. The signal level was found to be highly dependent on the position of the 2nd harmonic upper hybrid resonance:

$$\omega_{gyr} = 2\times\omega_{UH} = 2\times\sqrt{\omega_{pe}^2+\omega_{ce}^2}$$

The anomalous signal was maximized at magnetic fields and electron densities which placed the 2nd harmonic upper hybrid resonance at the island position on the plasma low field side. There, the anomalous scattering was strongly correlated with the passage of the island O-point through the ECRH beam (Fig 2). The spectrum responded sensitively to small changes in electron density. For higher density the frequency shifts became larger and the fraction of the island cycle which contained anomalous signal was increased.

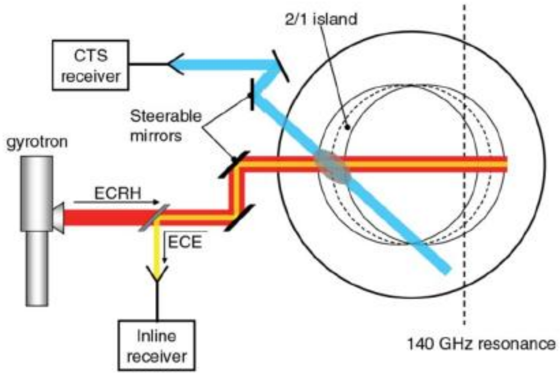

Fig. 1. Schematic setup of the scattering experiments on the TEXTOR tokamak. Reproduced from [Westerhof 2009].

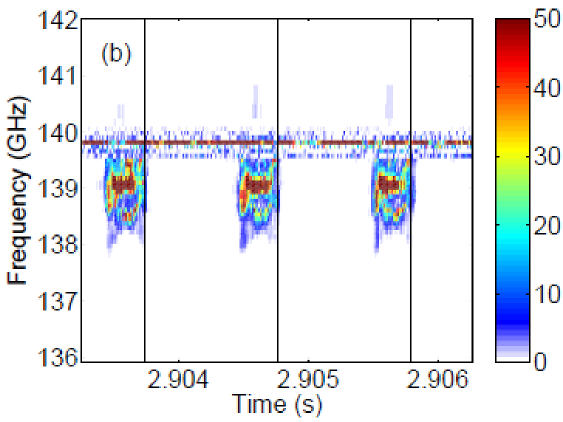

Fig. 2. Example of measured spectral evolution (in MeV) during individual island passages. Each island passage is indicated by a vertical line.

The strong scattering signals were obtained for toroidal gyrotron injection angles from -8 to 20 degrees. When the resolved fluctuation wave vector, $\mathbf{k}^{\delta} = \mathbf{k}^{s}-\mathbf{k}^{i}$, is perpendicular to the magnetic field, **B**, thermally driven ion Bernstein waves can be observed in the scattering spectra [Stejner 2013] ($\mathbf{k}^{i}$ and $\mathbf{k}^{s}$ are the wave vectors of the incident and scattering radiation, respectively). However, in the present case the angle between $\mathbf{k}^{\delta}$ and **B** spanned from 65 to 105 degrees ruling out that thermally driven ion Bernstein waves are responsible for the strong scattering. Finally the signal was measured to be localized in space inside the tokamak which rules out that the signals are being produced in the gyrotron cavity.

On ASDEX Upgrade, recent experiments using a 105 GHz gyrotron for central 2nd harmonic X-mode heating have confirmed the relationship between the strong scattering and the second harmonic upper hybrid resonance. Here 600 kW of ECRH power was injected into a plasma with an on-axis toroidal magnetic field of 1.9T placing the 2nd harmonic electron cyclotron resonance in the plasma centre and the 2nd harmonic upper hybrid resonance close to the plasma edge (Fig. 3). One of the CTS receivers at ASDEX Upgrade was used for detection of the anomalous scattering [Furtula 2012]. The signal was attenuated using a voltage controlled variable attenuator (VCVA) and the system was cross-calibrated to the ECE diagnostic. The direction of the receiver plasma-facing mirror was modified during the discharge such that the view was swept *along* the gyrotron beam during a plasma period without the presence of islands. At t=1.9s the receiver beam intersects the gyrotron beam in the vicinity of the upper hybrid resonance. At this time a significant increase in the signal is observed by many of the receiver channels (example shown in Fig. 4). The receiver sweep continued to the plasma edge and the anomalous signal amplitude decreased. The receiver view was moved back to the upper hybrid position and the anomalous signal level was re-obtained. Later in the discharge a 2/1 mode was triggered which increased the signal amplitude and the frequency complexity significantly.

The signals from TEXTOR are likely to be caused by the parametric decay instability (PDI) where the primary gyrotron wave decays into a high frequency and a low frequency daughter wave [Gusakov 2010]. The measured scattering signal is mainly down shifted in frequency and the amplitude is highly non-linear with respect to the gyrotron power as expected in the PDI scenario. The results from ASDEX Upgrade contain similar signatures as the TEXTOR results. In future experimental campaigns on ASDEX Upgrade we hope to investigate the signal dependence on density and magnetic field in more detail. Specifically we plan to identify the low frequency daughter wave which will confirm that the parametric decay instability is the mechanism responsible for the anomalous scattering.

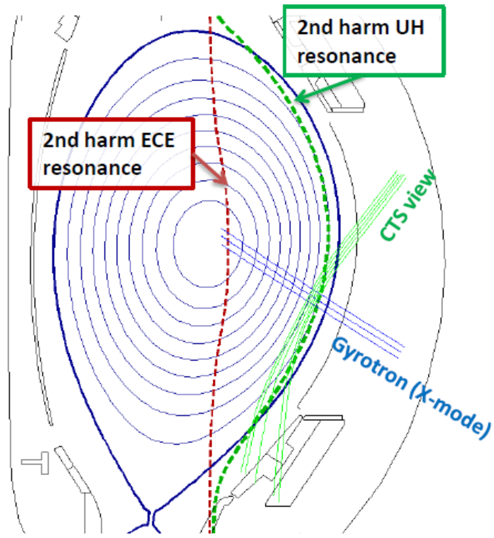

Fig. 3. Ray tracing from the ASDEX upgrade tokamak. At t=1.9 s, the beam of the 105 GHz heating gyrotron (blue) crosses the CTS receiver view (green) at the second harmonic upper hybrid resonance (green dashed line). This geometry maximizes the anomalous signal measured by the receiver. The second harmonic electron cyclotron resonance (red dashed line) is optically thick for X-mode.

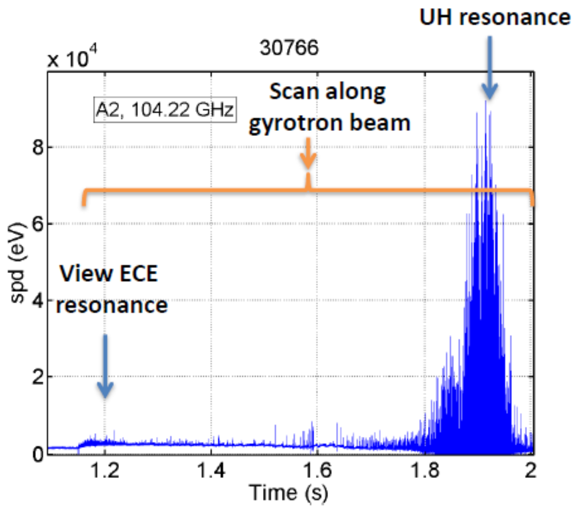

Fig. 4. Time trace of signal at 104.22 GHz in the CTS receiver A2 at ASDEX Upgrade during a receiver sweep along the 105 GHz gyrotron beam.

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